Measuring the Cosmic Equation of State with Galaxy Clusters in the DEEP2 Redshift Survey

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ABSTRACT

The abundances of groups and clusters of galaxies are expected to have changed substantially since high redshift, with the strength of this evolution dependent upon fundamental cosmological parameters. Upcoming large redshift surveys of distant galaxies will make it possible to measure these quantities at $z \sim 1$; when combined with the results of local redshift surveys currently underway, the evolution of cluster abundances may be determined. The DEEP2 Redshift Survey, planned to begin in Spring 2002, is particularly well-suited for this work because of the high spectroscopic resolution to be used; velocity dispersions of groups will be readily measurable. In this paper, we determine the constraints on dark energy models that counts of clusters within the DEEP2 survey should provide. The velocity function of clusters may be predicted directly in the extended Press-Schechter framework. We find that comparing cosmological models using the simultaneous distribution of clusters in both velocity dispersion and redshift yields significantly stronger constraints than the redshift distribution alone. The method can be made more powerful by employing a value of the fluctuation amplitude σ_8 determined with upcoming techniques (external to DEEP2) that have no Ω_m degeneracy. The equation-of-state parameter for dark energy models, $w = P/\rho$, can then be measured to ± 0.1 from observations of clusters alone.

Subject headings: cosmological parameters, cosmology: observations, galaxies: high-redshift, galaxies: clusters: general

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1. Introduction

In two previous papers (Newman & Davis 2000, hereafter ND00, and Newman & Davis 2001, hereafter ND01), we described a new variant of the classical "dN/dz" test that could measure fundamental cosmological parameters using data from the next generation of redshift surveys. By measuring the apparent abundance of galaxies as a function of their linewidth or velocity dispersion rather than luminosity or other properties, we may exploit the simplicity of the velocity function of dark matter halos and avoid many of the uncertainties that result from the physics of galaxy formation. Combining measurements of the velocity function at low and high redshift yields the evolution of the cosmic volume element, which depends upon fundamental cosmological parameters in a simple fashion. This is not the only form of the dN/dz test to be considered in recent years, however.

In particular, because clusters of galaxies are rare, particularly at high redshift, their number density is exponentially sensitive to the rate of growth of large-scale structure. Their observed abundance thus can place limits on fundamental cosmological parameters (Lilje 1992). For instance, Haiman, Mohr, & Holder (2001) found that the observed numbers and redshift distributions of galaxy clusters discovered in future X-ray or Sunyaev-Zel'dovich (S-Z) surveys could impose strong constraints on the cosmic equation-of-state parameter of quintessence-like dark energy models, $w = P/\rho$. However, because it relies on counting the total number of clusters above some minimum mass, a rapidly decreasing function, their method requires the mass limit for finding clusters in such surveys to be very well-understood. They find that the mapping between the matter power spectrum and the masses of clusters leads to a further dependence on the Hubble parameter, the value of which is still only known to $\sim 10\%$ (Freedman *et al.* 2001).

In this paper, we propose another form of this test which will be possible using data from the same galaxy redshift surveys as the method of ND00. Just as it is possible to count galaxies as a function of their circular velocity rather than their optical luminosity, we can count galaxy clusters as a function of their velocity dispersion rather than their X-ray luminosity or S-Z decrement. By performing the test on the differential velocity function rather than the integrated count above some mass, we do not require perfect knowledge of the survey characteristics to produce results. Furthermore, by studying clusters as a function of their velocity dispersions rather than their masses, we can avoid the sensitivity to the Hubble parameter present in other methods.

Specifically, we present here the constraints upon cosmological parameters which the DEIMOS/DEEP (hereafter, DEEP2) Redshift Survey will provide (Davis *et al.* 2000). This project is intended to obtain data on large samples of distant galaxies using the new DEIMOS spectrograph, which is scheduled to be installed in early 2002 at the Keck Observatory.

DEEP2 will obtain spectra of $\sim 60,000$ galaxies preselected from BRI photometry to have minimum redshift $z > 0.7$ (the "1HS", or 1-Hour Survey, so named because of the expected exposure time per slitmask). Four 2 deg $\times$ 1/2 deg fields have been selected for the 1HS, yielding a total volume (for the optimal redshift range of the survey, $0.7 < z < 1.5$) approaching $10^7 h^{-3}$ Mpc^3 in LCDM cosmologies. The 1HS will have a magnitude limit of $I_{AB} = 23.5$, roughly L_* at $z = 1$. Roughly 70% of the galaxies meeting the survey criteria will be targetable for observations (due to the technical constraints of slitmask spectroscopy), and secure redshifts are expected for $\sim$ 85% of the observed galaxies. In addition, longer-exposure spectra of $\sim 5,000$ galaxies to $I_{AB} = 24.5$ will be obtained in selected regions (roughly 10% of the total survey area), constituting the "3HS", or 3-Hour Survey. DEEP2 will obtain data characterizing galaxies and large-scale structure that are comparable to those provided by the best completed surveys of the local universe, but for objects at high redshift, $z \sim 1$, instead. Because of the high spectroscopic resolution (FWHM ~ 65 km s^{-1} at $z = 1$) and relatively dense sampling to be used, DEEP2 will be uniquely suitable for providing measurements of the velocity dispersions of galaxy clusters in the distant universe with no preselection. Other past or planned projects such as the VLT/VIRMOS survey and its subsamples (Lefevre 2000) only have sufficient redshift resolution to determine the velocity dispersions of only the most massive clusters, only cover small areas of the sky, and/or are likely to be less densely sampled than DEEP2 at $z \sim 1$ because of their shallower magnitude limits and lack of selection against low-redshift objects. As an additional advantage, sensitive S-Z observations are planned for all DEEP2 fields, which will allow the virialization state of clusters found to be assessed. In § 2 of this paper, we describe our calculations of cluster abundances, and in § 4, the resulting constraints upon fundamental cosmological parameters.

2. Calculations of cluster abundances

Narayan & White (1988) showed, under the assumption that structures observed are well-described by isothermal spheres and are just virializing, that the velocity dispersion distribution of dark matter halos may be calculated within the Press-Schechter (1974) framework as simply as the mass distribution. For this work, we apply their technique to the improved semianalytic mass function of Sheth & Tormen (1999), using the approximate relations of Bryan & Norman (1996; for those models with $w = -1$) or Wang & Steinhardt (1998) to determine the overdensity of collapsed structures compared to the background density, Δ_{vir}. We have fixed the power spectrum shape parameter $\Gamma = 0.25$ in our calculations. Given a value of the fluctuation normalization σ_8, the velocity dispersion distribution of dark matter halos in a given cosmology follows immediately; we assume here that the measured

velocity dispersions of the galaxies within clusters will follow the same distribution. Since clusters even today are dynamically very young, these assumptions are expected to work very well, and indeed are borne out in comparisons to N-body models (Springel *et al.* 2000).

In the following analysis, we consider two scenarios for the determination of the mass power spectrum normalization σ_8. In one, which we will label as "conservative", we assume that studies of galaxies and clusters in upcoming local surveys (such as 2dF and SDSS, Colless 1998, Loveday *et al.* 1998) will fix the power spectrum sufficiently that errors in cosmological parameters will be dominated by cosmic variance and Poisson statistics in the DEEP2 sample, but with the same parameter degeneracies that have affected past measurements. Since these surveys are much larger in volume and have higher sampling density than DEEP2, this is likely to be the case. Thus, in this scenario, for each cosmological model considered we use the results of Borgani et al. 1999 (in cases where we have fixed $w = -1$) or Wang & Steinhardt (1998) to assign values for σ_8 as Ω_m, Ω_Λ, and w vary, with zero error assumed.

In the other scenario, which we will term "optimistic," we presume that emerging techniques which fix σ_8 for the mass with no dependence on other cosmological parameters will be successful. For example, the 2dF and SDSS surveys will provide extremely accurate measurements of the correlation properties of nearby galaxies. Weak lensing analyses, by measuring either the mass in individual galaxy halos (e.g. McKay *et al.* 2001) or of the aggregate large-scale structure (Kaiser 1998) can then determine the bias between the correlation statistics of galaxies and of the underlying dark matter, allowing transformations from one to the other. From preliminary SDSS data, for instance, McKay *et al.* found that in the red optical bands (r, i, and z), the light of nearby galaxies traces the mass on scales up to 1 Mpc, and that the influence of groups is clear. If weighted by luminosity in these bands, galaxy correlation measurements should then provide an accurate estimator of the mass correlation function, and thus of σ_8. Measurements on non-linear scales may be reliably connected to the equivalent linear amplitude using the methods of Hamilton *et al.* (1991). If σ_8 has been determined from such external data, we can use the abundances and velocity functions of local clusters in conjunction with those at high redshift to set better constraints on cosmological parameters.

It is necessary to note that the Press-Schechter framework upon which these calculations are built relies upon the Gaussianity of fluctuations in the matter density. If that fundamental assumption fails, the abundances of clusters at high redshift, which lie on the extreme tail of the probability distribution for density, may differ radically from Gaussian predictions. In that case, the observed abundances of clusters in DEEP2 will place few constraints on cosmological parameters, if any, but could provide strong information on cosmological non-

Gaussianity (Robinson & Baker 2000).

3. Cosmological constraints

Given the methods for calculating the abundance of clusters described in §2, we may compare the predictions of various models for the observed number of clusters per unit redshift and solid angle to determine what constraints on cosmological parameters will be possible from DEEP2. This may either be done integrally (comparing the total number of clusters above some velocity dispersion observed in different redshift intervals, $\mathrm{d}N(>\sigma)/\mathrm{d}z$, to the predictions for a model) or differentially (using the distribution of clusters in velocity dispersion as well as redshift, $\mathrm{d}N/\mathrm{d}\sigma\mathrm{d}z$, to set constraints). We have therefore calculated the comoving abundance of clusters over dense grids in velocity dispersion, redshift, and cosmological parameters (Ω_m and Ω_Λ for models with $w = -1$, or Ω_m and w for models assumed to be flat). The grid spacings used are sufficient to allow determination of the integrated abundance of clusters in ten 50 km s^{-1} velocity dispersion bins from 300 to 800 km s^{-1} (along with an eleventh bin for clusters with velocity dispersions from 800 to 1000 km s^{-1}, beyond which very few objects are predicted to exist) and in 8 bins spanning z =0.7 to 1.5, each covering 0.1 in redshift. The results may then be multiplied by the amount of volume in each redshift bin for the DEEP2 survey in the given cosmology to yield a prediction for the observed number of clusters in each bin. For the optimistic scenario, we have also calculated the expected observed abundance of clusters in each model for a survey spanning $0 < z < 0.1$ covering one-fourth of the sky (using the velocity function at $z = 0.05$), similar to what one might expect for the densely sampled portion of the SDSS Redshift Survey (Loveday *et al.* 1998).

Poisson variance should be the dominant source of uncertainty in a measurement of the abundance of clusters with DEEP2. In an LCDM model, less than a thousand clusters with velocity dispersions above 400 km s^{-1} are expected to exist in the survey volume; considerably fewer should be found in any of the redshift/velocity bins. For the lowest-velocity, most abundant clusters, a comparable error may arise from cosmic variance, the excess fluctuations in counts of cosmological objects that occur because of large-scale correlations. Unlike Poisson variance, this uncertainty will be correlated in every velocity bin within the same redshift interval. We have used here the DEEP2 cosmic variance calculations of ND01 rescaled to a value of $\sigma_8 = 1.8$, which matches the amplitude of fluctuations of 400 km s^{-1} clusters at $z \sim 1$ expected from their predicted correlation length in an LCDM model (Colberg *et al.* 2000).

Any application of the cluster $\mathrm{d}N/\mathrm{d}z$ test may be subject to a variety of systematic

effects: the identification of clusters and the measurement of their velocity dispersions in an unbiased way are inherently difficult, even at low redshift (see, for instance, Giuricin *et al.* 2000). Clusters are not actually the isothermal spheres we have assumed in the velocity function predictions, nor do galaxies precisely trace the dark matter potential of clusters. However, in actually performing a $\mathrm{d}N/\mathrm{d}z$ measurement, one can be guided by comparisons to the results of N-body simulations, in which clusters may be found and counted with the same systematics that affect DEEP2 observations, instead of using simple semi-analytic predictions. We thus believe this is not likely to be a crippling problem. So long as the measurement errors (or the errors due to any systematics) in the velocity dispersions of the clusters are known from theory or tests with simulations, those errors may be applied to the predictions of each cosmological model before comparison to observations. With sufficient theoretical effort towards determining the relationship between the observed properties of clusters and their intrinsic characteristics, the constraints presented here could be achieved; we focus on the limits of what will be possible with the data. We have reason to be optimistic; Marinoni *et al.* (2001) find that new cluster identification and membership determination algorithms, when applied to mock DEEP2 catalogs drawn from the VIRGO/GIF simulations enhanced with semianalytic techniques, can reconstruct the actual cluster velocity function from observations down to a velocity dispersion of 300 km s^{-1}.

For clusters found in a large local survey, cosmic variance is negligible; the volume considered is orders of magnitude higher than that in any DEEP2 redshift bin. The number of clusters in all but the most extreme velocity bins will accordingly be large as well. We thus may expect that systematic errors are more likely to dominate over Poisson errors than they are at high redshift. For constraints at low z, we therefore have conservatively required the uncertainty assigned to the abundance in each redshift/velocity bin to be at least 5%, with the Poisson value used if it is larger than that.

Given the above definitions, the covariance matrix amongst the redshift and velocity bins is fully determined (as Poisson variance is uncorrelated in both redshift and velocity, while the cosmic variance yields a completely correlated fractional error amongst velocity bins at the same redshift, but is nearly uncorrelated between different bins of 0.1 in z). We may then calculate χ^2 between any model and some nominal, "true" model (e.g. LCDM: $\Omega_m = 0.3, \Omega_Q = 0.7, w = -1$) in either the conservative or the optimistic scenario.[2] Observed results should be distributed as χ^2 with two degrees of freedom, so contours of χ^2 may be immediately transformed into statistical confidence constraints.

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[2]We use the extension of χ^2 to a multivariate distribution with covariance: $\chi^2 = (\mathbf{n} - \mathbf{n_0})^{\mathbf{T}}\mathbf{V^{-1}}(\mathbf{n} - \mathbf{n_0})$, where $\mathbf{n}$ is the vector of observations, $\mathbf{n_0}$ is the vector of true values, and $\mathbf{V}$ is the covariance matrix for $\mathbf{n_0}$.

In Fig. 1 we show the results of these calculations for the conservative scenario, assuming that clusters may be reliably found down to a velocity dispersion of 400 km s^{-1} (the actual limits will depend upon our ability to identify and measure the characteristics of small clusters; see Marinoni *et al.* 2001). Measuring the distribution of clusters in both velocity dispersion and redshift rather than using only $\mathrm{d}N(>\sigma)/\mathrm{d}z$ yields substantially stronger parameter measurements. We have also plotted in this figure the "best bet" contours from ND01. This method is subject to completely different systematic effects, providing an excellent consistency check. As shown in Fig. 2, using the optimistic σ_8 normalization yields much stronger constraints than any of those presented in Fig. 1, especially if $z \sim 0$ information is used. In that case, the value of w may be determined to better than 10% from cluster observations alone. We have also plotted for comparison the target 95% contours (statistical errors only) for observations of 2000 distant SNe Ia by the SNAP satellite (Perlmutter *et al.* 2000). A precision determination of Ω_m such as that obtained in the optimistic scenario would be highly complementary to the SNAP observations, yielding much stronger constraints on cosmological parameters; in the absence of a precision measurement of Ω_m, SNAP and DEEP2 cluster constraints on w would be quite comparable, but with very different systematics. Fig. 3 depicts the constraints set by DEEP2 for a model with $w = -0.7$. As is true for many methods (e.g. observations of SNe Ia at high redshift; see Huterer & Turner 2001), cluster $\mathrm{d}N/\mathrm{d}\sigma\mathrm{d}z$ observations yield much weaker constraints on w if its value is not -1; however, DEEP2 galaxy $\mathrm{d}N/\mathrm{d}z$ observations provide a very useful complementary constraint, yielding in combination a measurement of w to $\sim 10\%$.

Fig. 4 shows the dependence of the constraints upon the minimum velocity dispersion measured. In the optimistic scenario where low and high redshift clusters are studied, the constraints are nearly identical if only clusters above 500 km s^{-1} are considered as if clusters are observed down to a dispersion of 300 km s^{-1}. Although at $z \sim 1$ there are only $\sim 10\%$ as many clusters above 500 km s^{-1} as above 300 km s^{-1} ($\sim$ 300 versus $\sim$ 3000 in an LCDM model), even in the conservative scenario the constraints are only modestly weaker. Because of the strong dependence of their abundance upon the rate of growth of structure, the largest, rarest clusters have a weight in determining cosmological parameters that is disproportionate to their abundance. Large, local surveys should be very effective for finding these extreme clusters. On the other hand, the volume surveyed by DEEP2 is sufficiently small that only $\sim$ 10 clusters above 800 km s^{-1} velocity dispersion will be observed, so it is less possible to exploit their exponential sensitivity to the growth of structure from DEEP2 alone. Although they will be unable to detect the smaller DEEP2 clusters and groups, upcoming S-Z experiments will be capable of finding massive objects over much larger areas, $\sim$ 1000 deg^2 (Holzapfel 2001). With suitable follow-up observations, they S-Z results could be used to tighten further the potential constraints obtained from the velocity dispersion

and redshift distributions of DEEP2 clusters presented here.

Even if the value of σ_8 used in the optimistic scenario is uncertain, useful constraints on cosmological parameters may be obtained. In Fig. 5, we show the results of an error in σ_8 of $\pm 5\%$. As would be expected from previous parameter measurements based upon local clusters (e.g Borgani et al. 1999), if an erroneous value of σ_8 is used, a statistically equivalent distribution of local clusters may still be obtained for some (also erroneous) value of Ω_m. However, the high-redshift contours respond very differently; the primary change to the combined constraint is an offset of $\sim 10\%$ in the best-fit values of Ω_m and Ω_Λ or w. The increased precision afforded by the optimistic normalization makes the sensitivity of the measurement to the determination of σ_8 of equal or even greater importance than statistical errors.

In conclusion, we find that counts of clusters observed in the DEEP2 Redshift Survey have the potential to provide significant constraints on cosmological parameters, particularly when combined with both a non-cluster constraint on σ_8 and measurements of the local cluster velocity function. The data have sufficient power that the utility of this test is likely to be limited by our theoretical understanding and simulation capabilities rather than the observations. DEEP2 cluster constraints can be complementary to a variety of other tests that have been proposed, including not only studies of SNe Ia at high redshift or counts of clusters found by their S-Z decrement, but also galaxy $\mathrm{d}N/\mathrm{d}z$ measurements that the DEEP2 survey will make possible. By comparing and combining the results of very different methods of determining cosmological parameters, we may both obtain stronger constraints than any method alone would provide and test techniques against each other to identify signatures of systematic effects. In a field so afflicted by systematic errors as cosmology, having many complementary techniques is the best way to ensure that our framework of measurement holds together.

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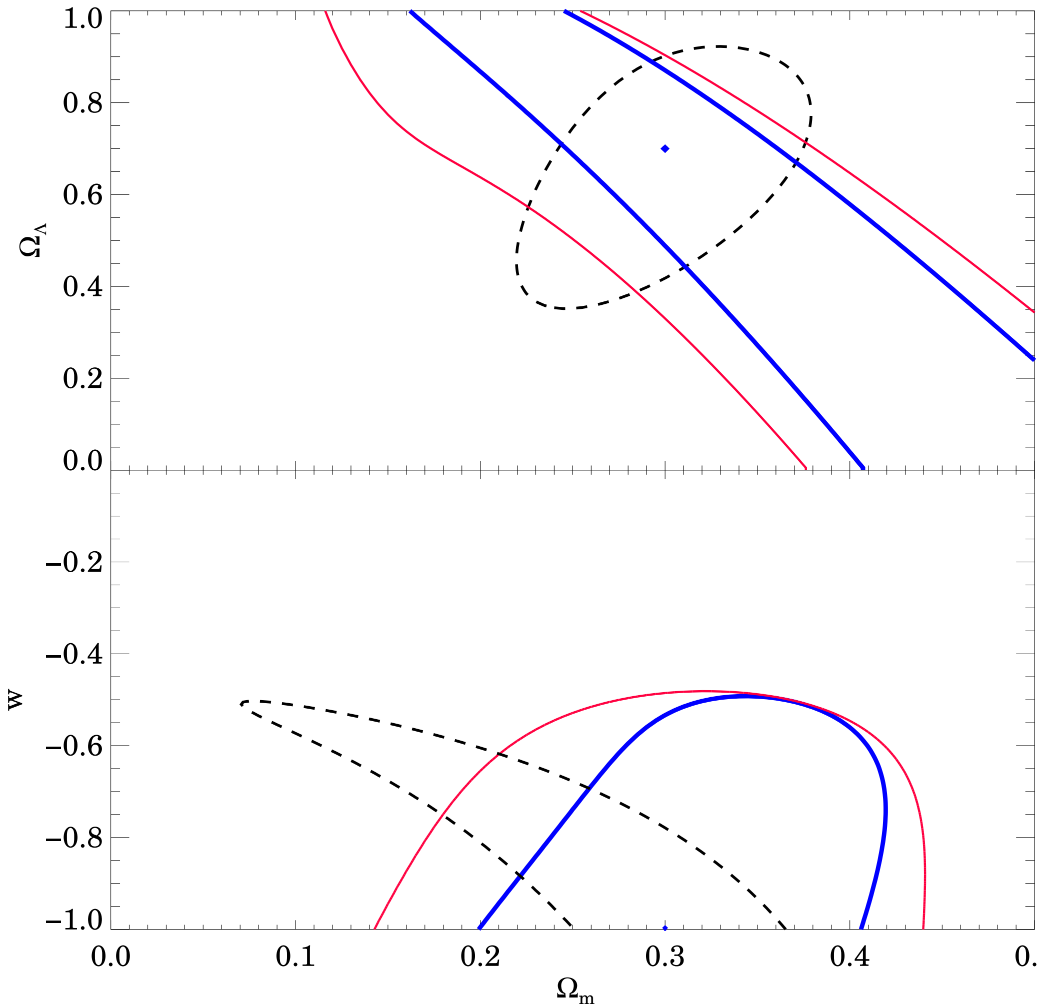

Fig. 1.— Expected constraints from a variety of cosmological tests made possible by the DEEP2 Redshift Survey, plotted for an LCDM model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $w = -1$ (indicated on all plots by a small blue diamond). All contours are at the 95% confidence level. (Top panel) Constraints in the Ω_m–Ω_Λ plane. The black, dashed contour is the "best bet" constraint from galaxy $\mathrm{d}N/\mathrm{d}z$ measurements (see ND01 for details). We also plot two sorts of constraints from DEEP2 clusters above 400 km s^{-1} in the conservative scenario: the thick, blue contours show the results of utilizing the distribution of those clusters in both velocity dispersion and redshift, $\mathrm{d}N/\mathrm{d}\sigma\mathrm{d}z$, while the thin, red solid contours use only the integrated number of clusters above 400 km s^{-1} in each redshift bin, ignoring all differential information on the velocity function. (Bottom panel) As above, but for the Ω_m–w plane. (NOTE: When printed out on a black and white printer, "red" contours in these figures will appear grey while the "blue" contours will be nearly black. In that case, the line style may still be used to distinguish the curves).

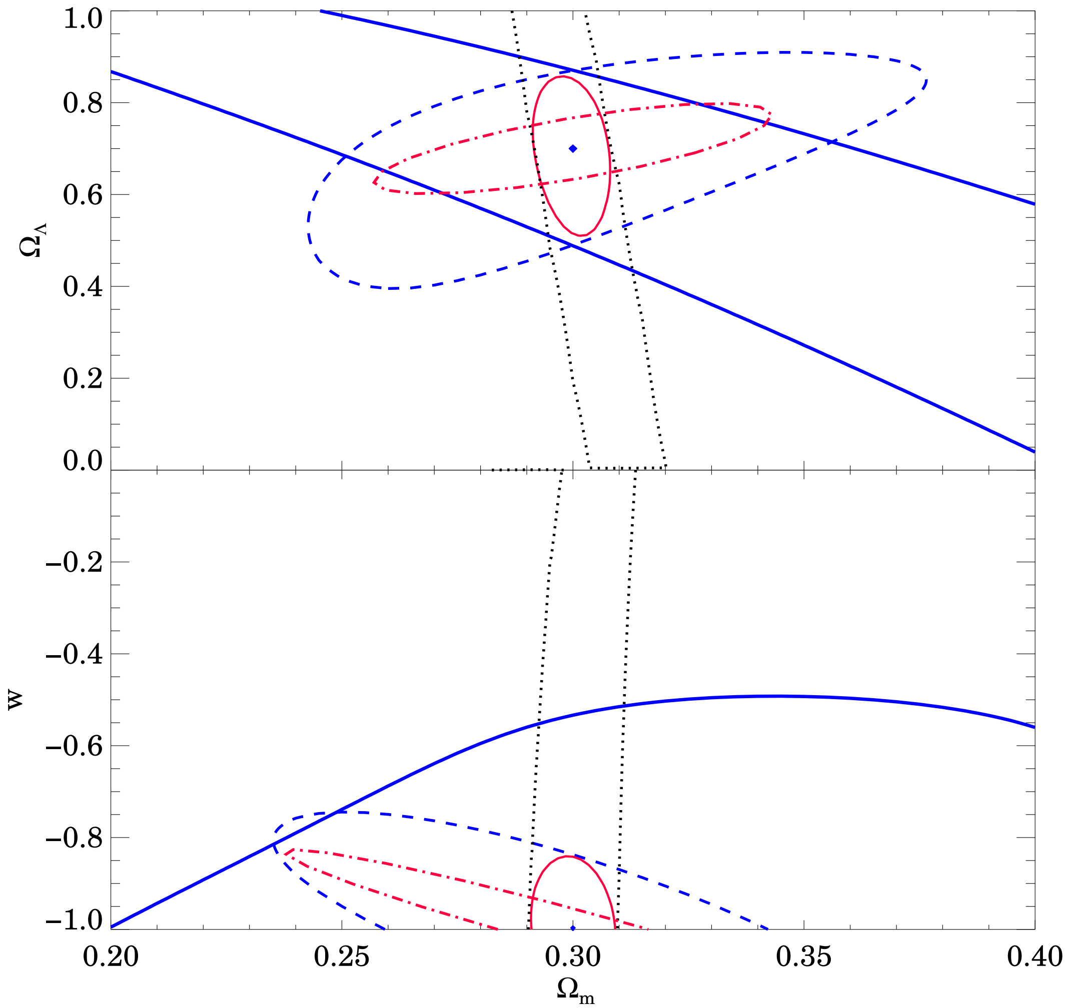

Fig. 2.— Cluster constraints on cosmological parameters obtainable using a variety of methods in an LCDM model. All contours are at the 95% confidence level. (Top panel) Constraints in the Ω_m–Ω_Λ plane (note that a more restricted range in Ω_m is plotted than in Fig. 1). As in the previous figure, the thick, blue contours show the constraints obtainable from $\mathrm{d}N/\mathrm{d}\sigma\mathrm{d}z$ in the conservative scenario. The dashed blue curves show the constraints from DEEP2 if the value of σ_8 for the mass is known with no other parameter degeneracies, while the dotted black contours show the constraints an SDSS-like survey could then provide from the velocity function of low-redshift clusters. The thin, solid red contours represent the optimistic scenario in which data from low redshift and high redshift may be used simultaneously to strengthen the constraints. The red, dot-dashed curves show for comparison the target 95% confidence intervals (statistical errors only) for the proposed SNAP satellite, a dedicated orbiting telescope to find SNe Ia at high redshift, taken from figures on the project's website (http://snap.lbl.gov). (Bottom panel) As above, but for the Ω_m–w plane.

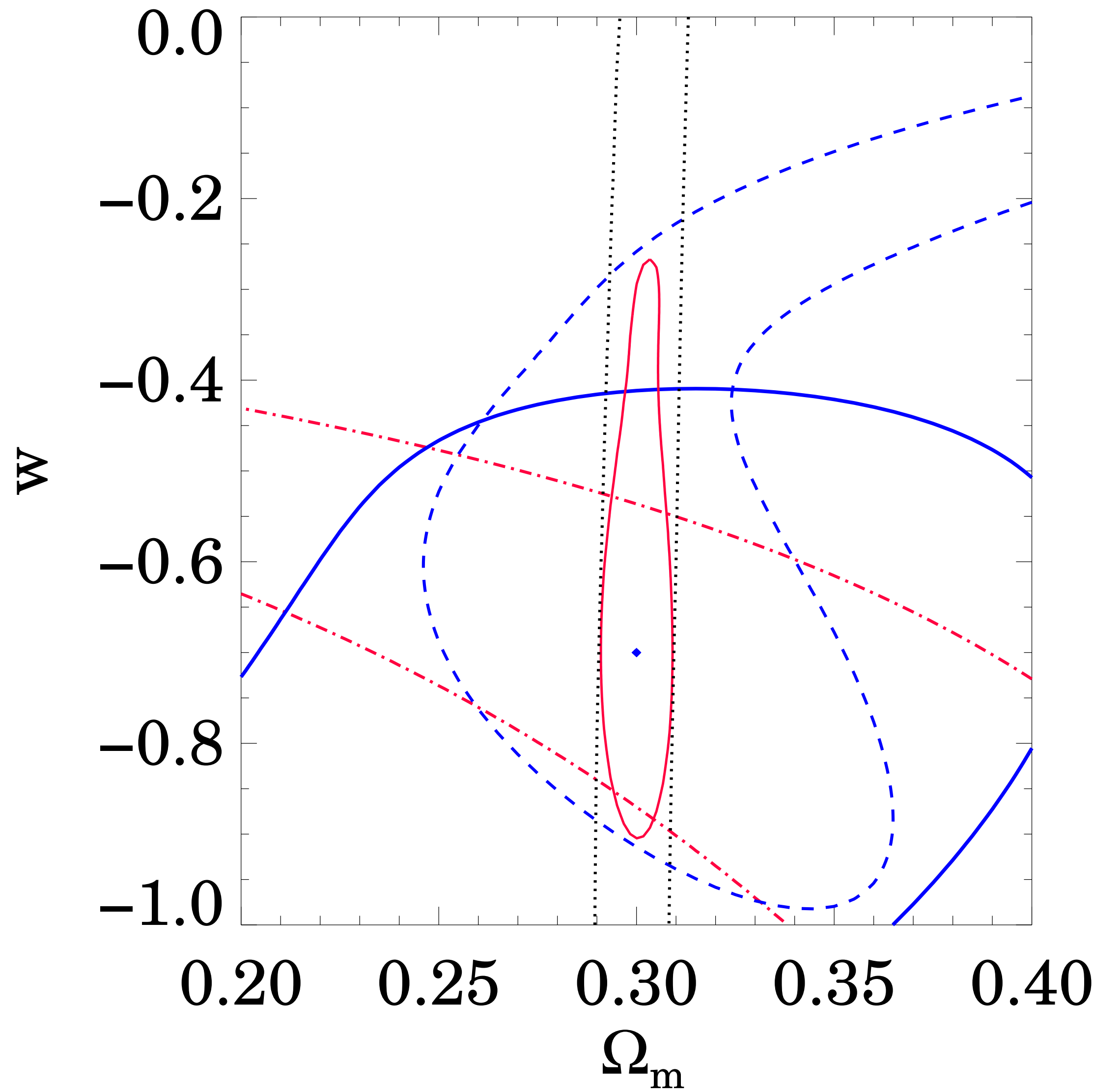

Fig. 3.— Cluster constraints on cosmological parameters obtainable using a variety of methods in a quintessence model with $\Omega_m = 0.3, \Omega_Q = 0.7, w = -0.7$. The solid, dashed, and dotted contours are all defined as in the preceding figure. The red, dot-dashed contour indicates the "best bet" constraint from DEEP2 galaxy $\mathrm{d}N/\mathrm{d}z$ measurements for this model, taken from ND01.

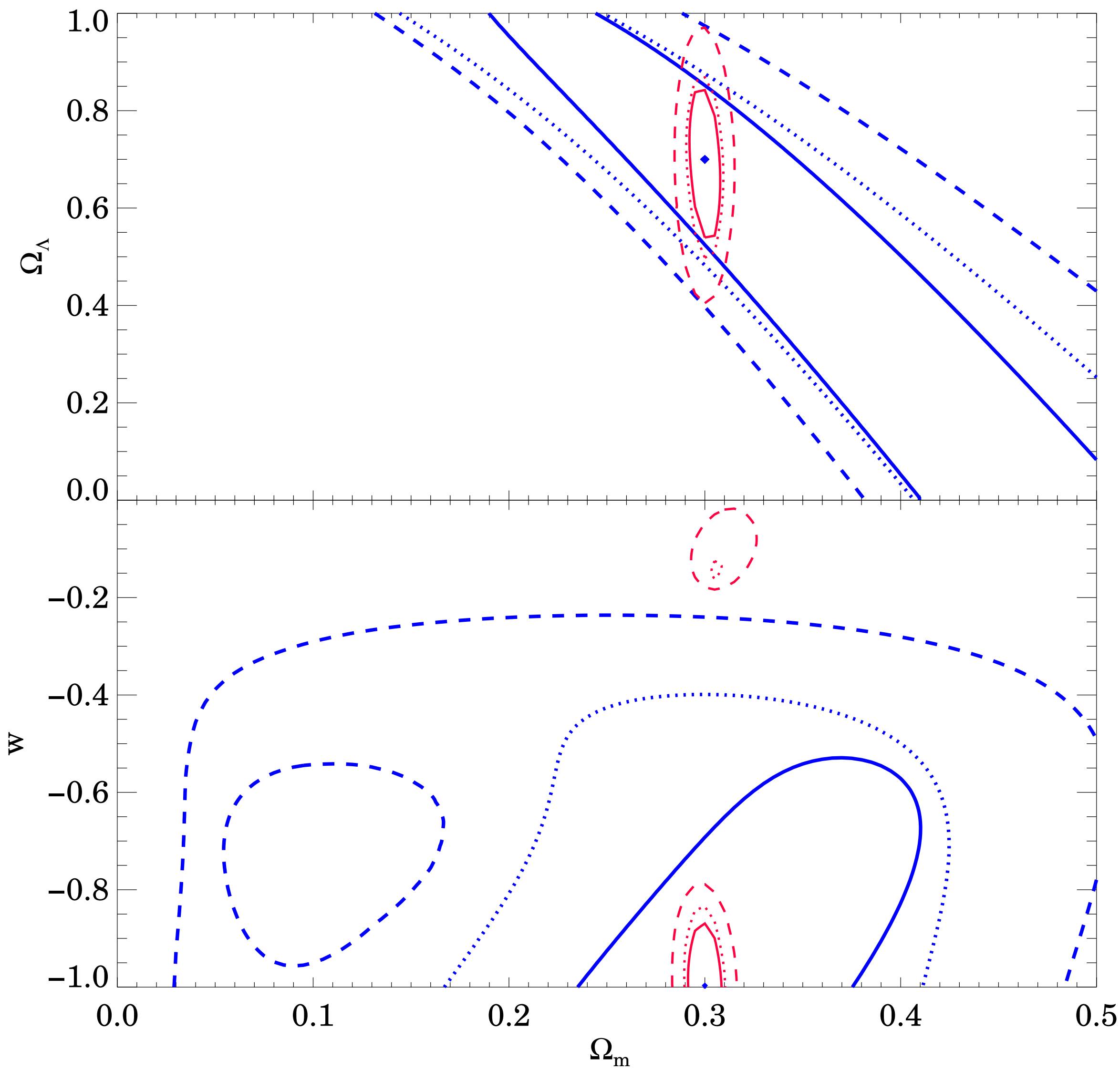

Fig. 4.— Variation of constraints plotted in Fig. 2 as the minimum velocity dispersion is changed. The blue contours show the DEEP2 constraints for an LCDM model in the conservative scenario, while the red contours indicate the combined low- and high-redshift constraints for the optimistic scenario. The solid, most optimistic contours are for the case where all velocity bins of dispersion > 300 km s^{-1} and above are used; the dashed, intermediate contours > 500 km s^{-1}; and the dot-dashed, weakest contours > 700 km s^{-1}. The two panels are defined as in Fig. 1. The degenerate solutions in the bottom panel with $w > -0.2$ are ruled out by other cosmological tests (Huterer & Turner 2001). Note that there is an excluded region within the conservative, $\sigma > 700$ km s^{-1} contour. Paradigms which simplify parameter constraints (such as Fisher matrix methods) completely fail to describe the contours for large minimum velocities.

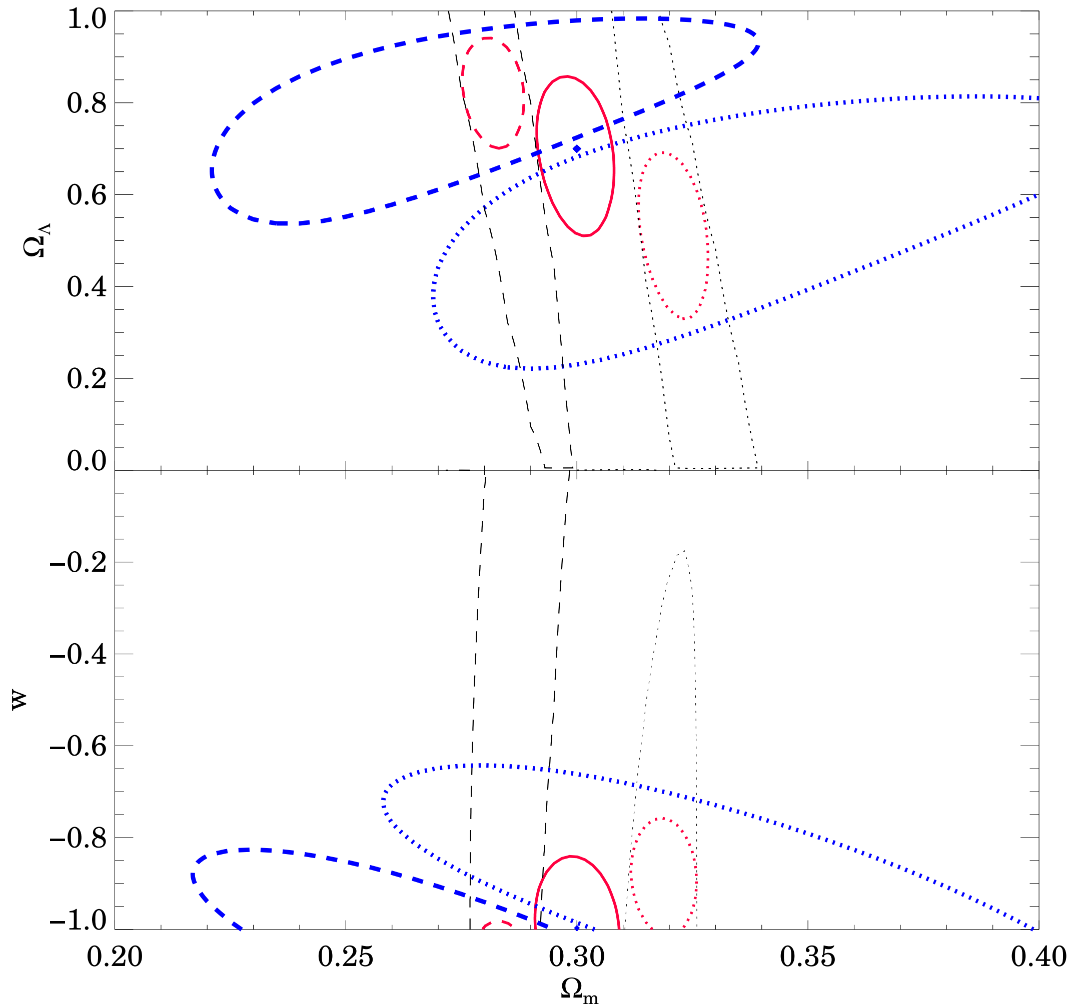

Fig. 5.— The variation of the DEEP2 cluster dN/dz constraints for an LCDM scenario if incorrect, fixed values of σ_8 are used (e.g., there is some systematic error in determining the bias, and thus also in σ_8 for the mass). The thin, black contours show constraints from $z \sim 0$ clusters alone; the thick, blue contours constraints from $z \sim 1$ clusters; and the red contours the combined constraints. For the dotted curves, a value of σ_8 that is too low by 5% has been used to determine constraints; for the dashed curvess, a value that is too high by 5%; and for the solid curves (for clarity, only plotted in the case of the combined constraint), the true value has been used. This figure covers the same restricted range of Ω_m depicted in Fig. 2.